Engineering Casimir forces with metamaterials

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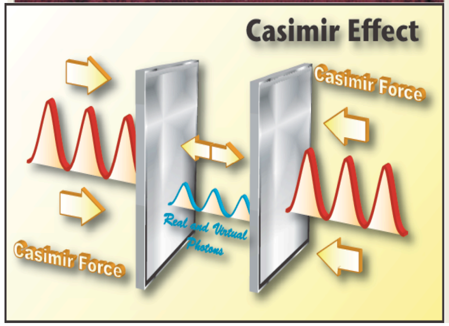
Outline of this talk

- Brief review of theory and experiments on the Casimir force
- Materials effects: Casimir repulsion with metamaterials
- Conclusions

Collaborators

Theory:	Peter Milonni (LANL)
	Felipe da Rosa (LANL)
Experiment:	Antoniette Taylor (CINT, LANL)
	Steve Lamoreaux (Yale)
	Ricardo Decca (Indiana)

The Casimir force



Casimir forces originate from changes in quantum vacuum fluctuations imposed by surface boundaries

They were predicted by the Dutch physicist Hendrik Casimir in 1948

Dominant interaction in the micron and sub-micron lengthscales

$$\boxed{\frac{F}{A} = \frac{\pi^2}{240}\frac{\hbar c}{d^4}} \qquad (130\mathrm{nN/cm^2} \ @\ d = 1\mu\mathrm{m})$$

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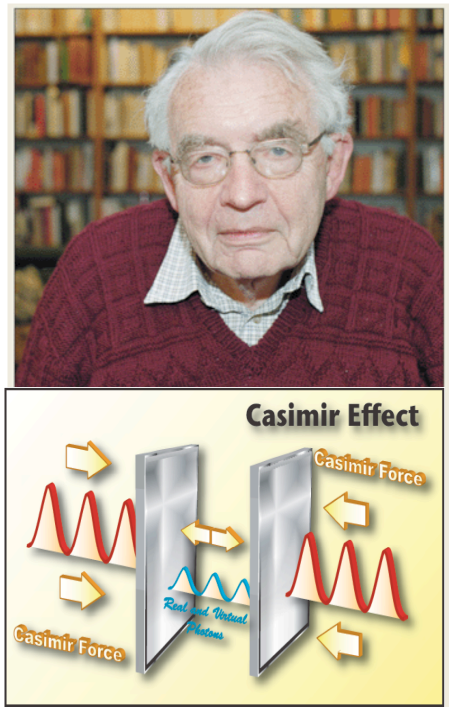

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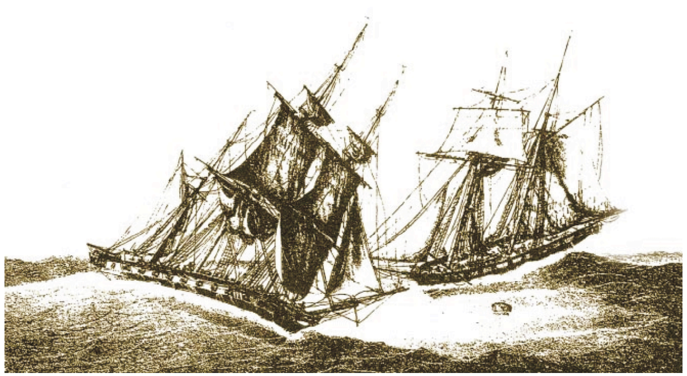
Classical Analog: L'Album du Marin (1836)

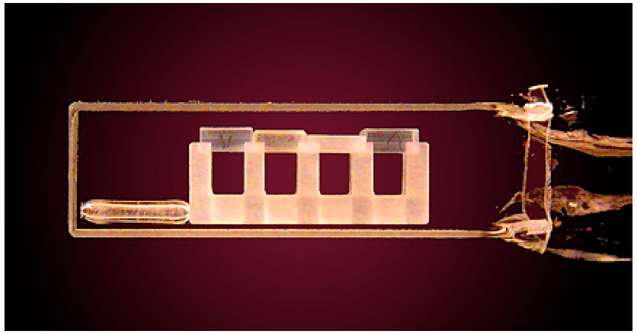


Relevant applications

- Quantum Science and Technology:

  Atom-surface interactions

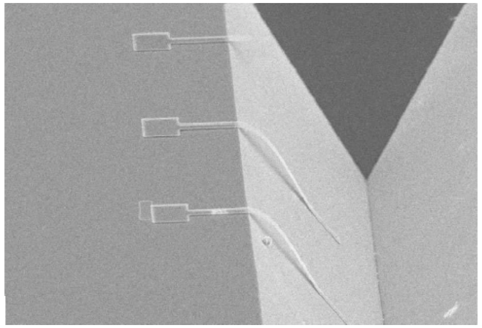
  Precision measurements



Cornell et al (2007)

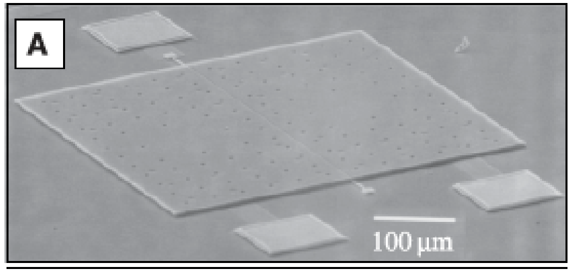
- Nanotechnology:

  Problems with stiction of movable parts in MEMS



Zhao et al (2003)

Actuation in NEMS and MEMS driven by Casimir forces



Capasso et al (2001)

Modern Casimir experiments

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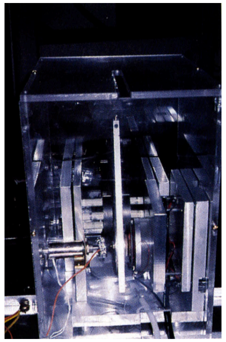
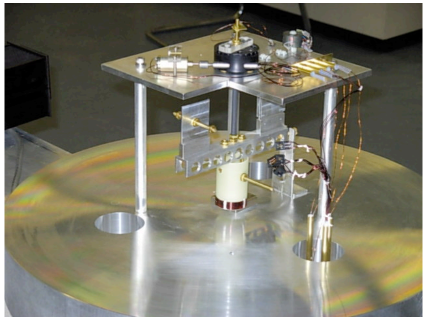
- Torsion pendulum





sphere-plane, d=1-10 um
Lamoreaux

Modern Casimir experiments

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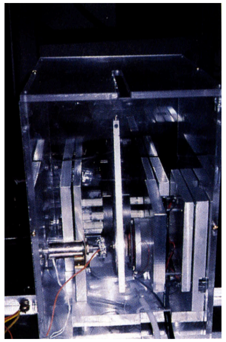

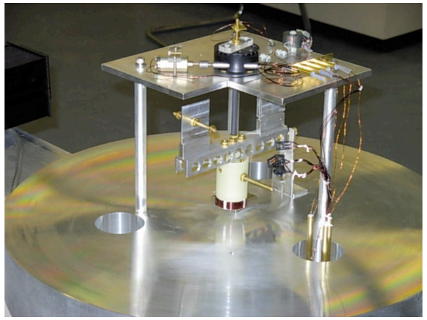

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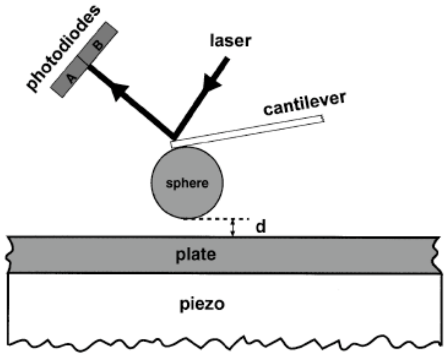
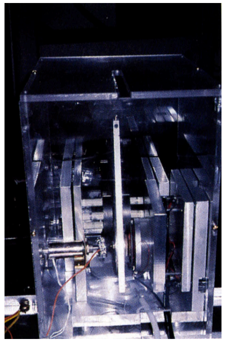
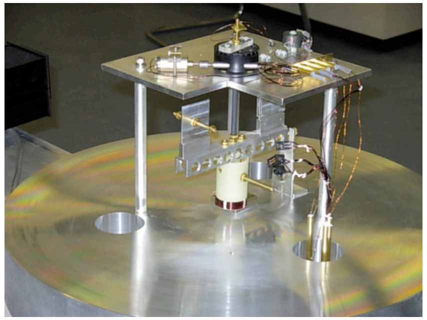
- Atomic force microscope



sphere-plane, d=200-1000 nm
Mohideen et al

Modern Casimir experiments

- Torsion pendulum

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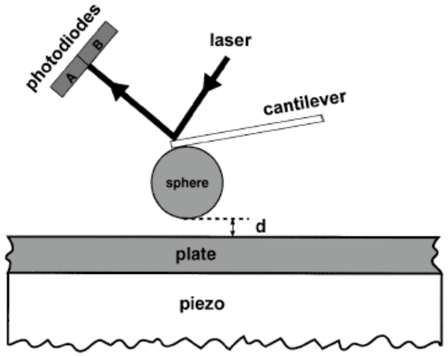
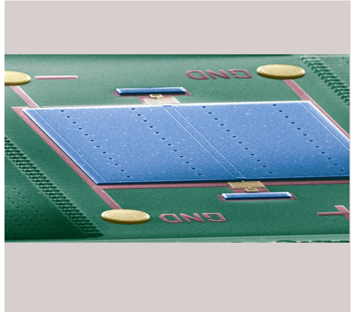


sphere-plane, d=200-1000 nm
Mohideen et al

- MEMS and NEMS



sphere-plane, d=200-1000 nm
Capasso et al, Decca et al

Modern Casimir experiments

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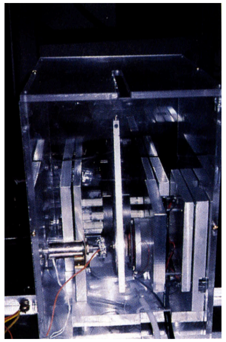

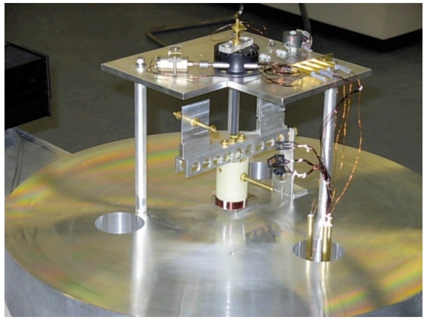

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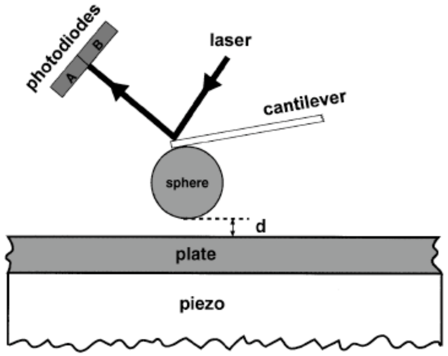

sphere-plane, d=200-1000 nm
Mohideen et al

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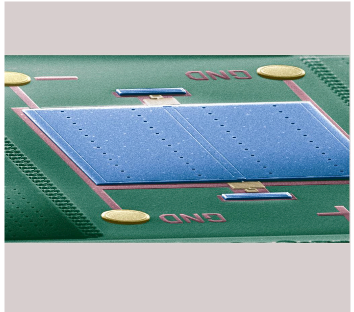
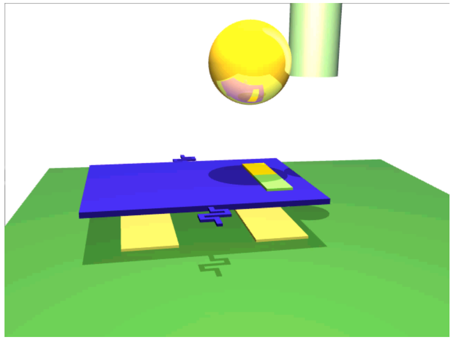
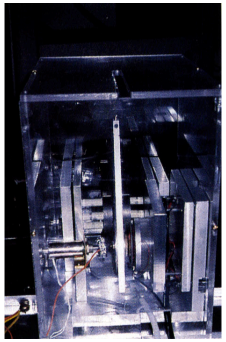
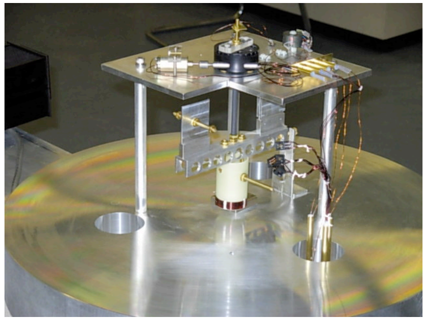




sphere-plane, d=200-1000 nm
Capasso et al, Decca et al

Modern Casimir experiments

Torsion pendulum

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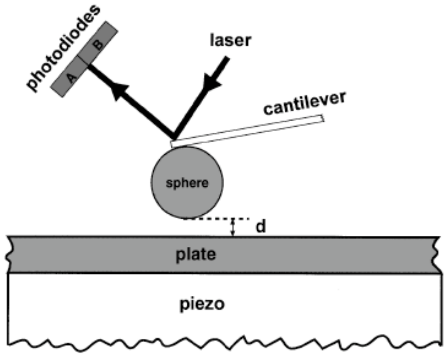

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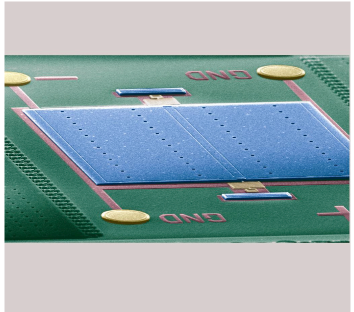
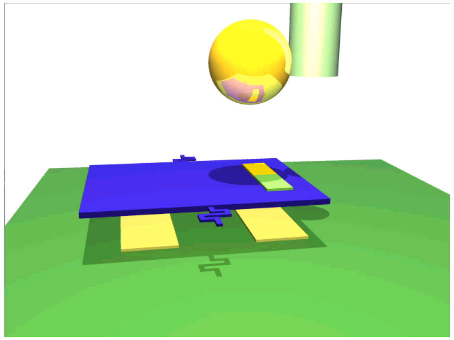
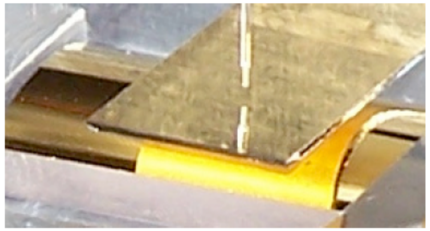
MEMS and NEMS

sphere-plane, d=200-1000 nm
Capasso et al, Decca et al

Micro-cantilever



plane-plane, cylinder-plane, d=1-3 um
Onofrio et al

Tailoring the Casimir force

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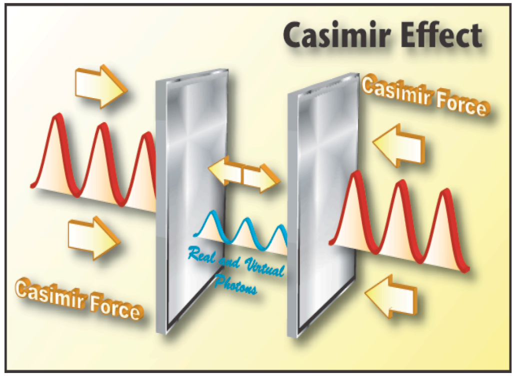
Magnitude and sign of the Casimir force depend on geometry and materials



Lifshitz formula: (assumes continuous and isotropic media)

$$\boxed{\frac{F}{A} = 2k_B T \sum_{n=0}^{\infty} \int_{\xi_n/c}^{\infty} \frac{d\kappa}{2\pi}\kappa^2 \sum_{\lambda=\mathrm{TE,TM}} \left(\frac{e^{2\kappa d}}{r_{\lambda_1} r_{\lambda_2}} - 1 \right)^{-1}}$$

Reflection coefficients:

$$r_\lambda(i\xi_n)$$

$$\omega_n = i\xi_n = 2\pi i n k_B T/\hbar$$

- Reflection coefficients at imaginary frequencies $\rightarrow$ Kramers-Kronig

$$\epsilon(i\xi_n) = 1 + \frac{2}{\pi}\int_0^\infty \frac{\omega\epsilon''(\omega)}{\omega^2+\xi_n^2} d\omega \qquad \mu(i\xi_n) = 1 + \frac{2}{\pi}\int_0^\infty \frac{\omega\mu''(\omega)}{\omega^2+\xi_n^2} d\omega$$

- The gap d sets a cut-off frequency: $i\xi_{\mathrm{cut-off}} \simeq c/d$

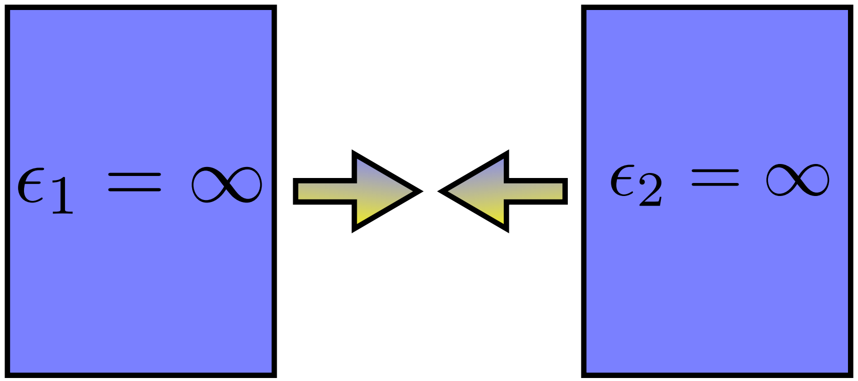
  For $d = 200\mathrm{nm} - 1\mu\mathrm{m}$ $\rightarrow$ frequencies in the near-infrared/optical

Casimir attraction-repulsion

- Ideal attractive limit

Casimir 1948

$$\boxed{\frac{F}{A} = +\frac{\pi^2}{240}\,\frac{\hbar c}{d^4}}$$



Casimir attraction-repulsion

- ## Ideal attractive limit

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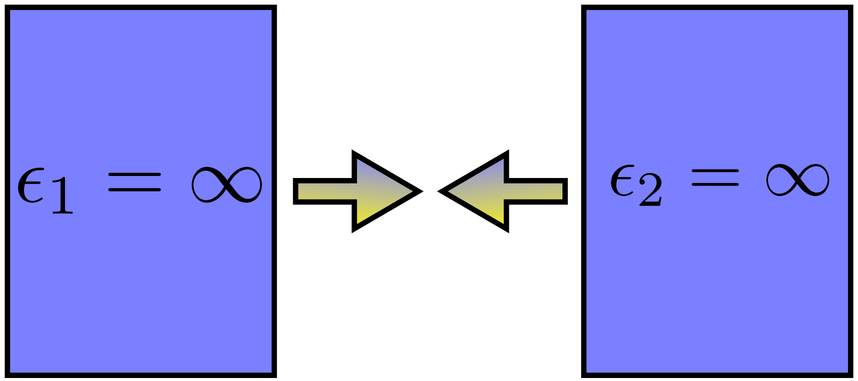
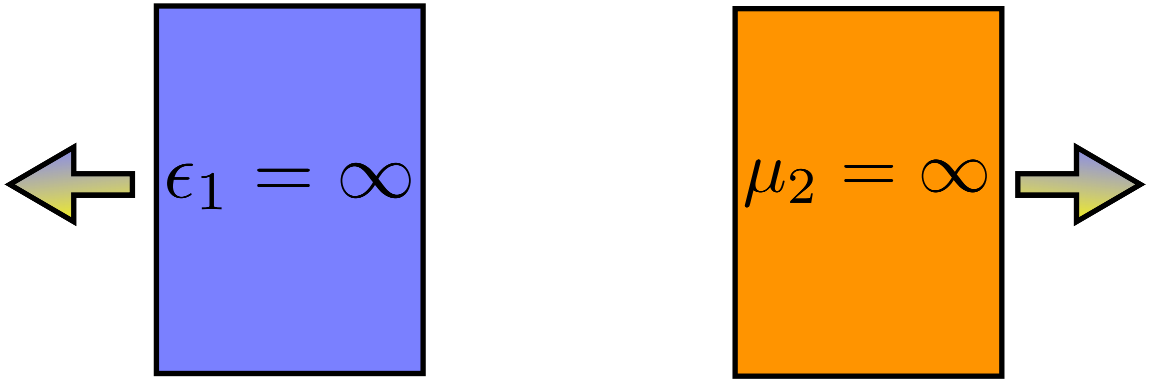


- ## Ideal repulsive limit

Boyer 1974

$$\boxed{\frac{F}{A} = -\frac{7}{8}\,\frac{\pi^2}{240}\,\frac{\hbar c}{d^4}}$$



Casimir attraction-repulsion

- **Ideal attractive limit**

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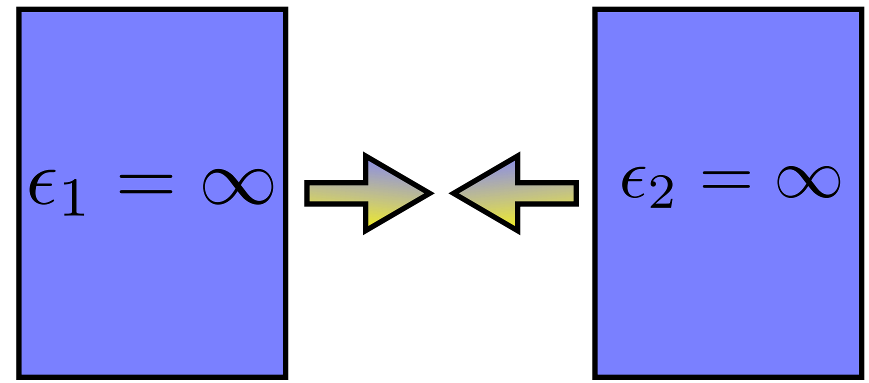

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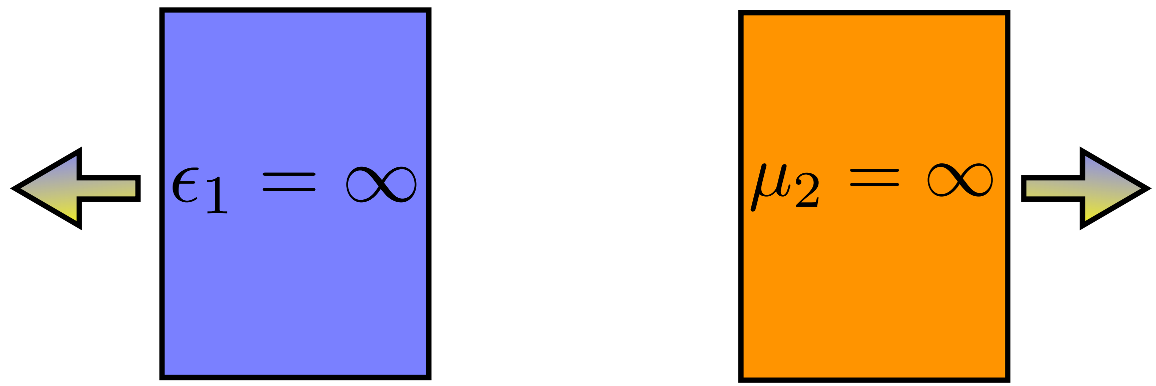

- **Real repulsive limit** $\epsilon(i\xi) < \mu(i\xi)$

  Casimir repulsion is associated with strong electric-magnetic interactions. However, natural occurring materials do NOT have strong magnetic response in the optical region, i.e. $\mu = 1$

Casimir attraction-repulsion

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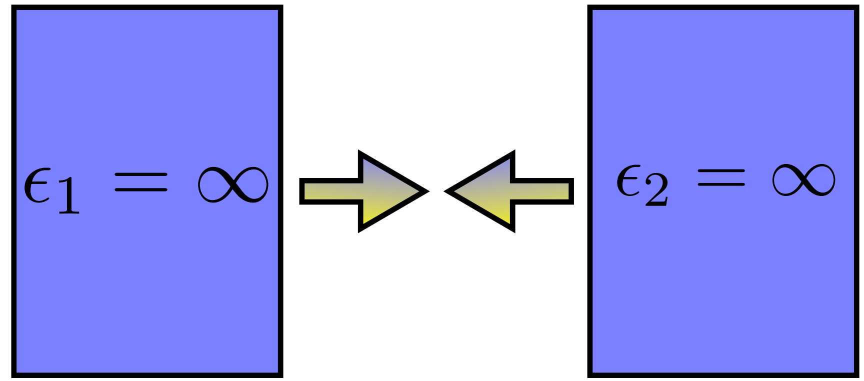

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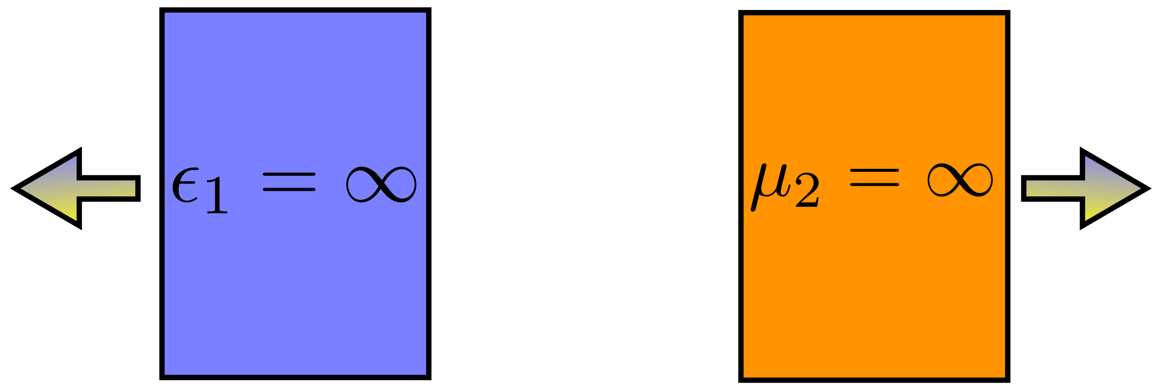

- ## Real repulsive limit $\epsilon(i\xi) < \mu(i\xi)$ $\longrightarrow$ Metamaterials

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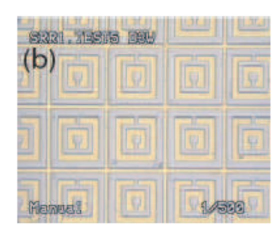

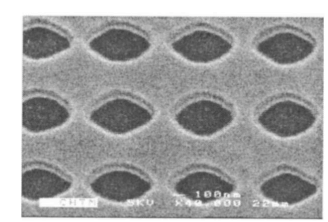

Quantum levitation with MMs?

Physicists have 'solved' mystery of levitation - Telegraph http://www.telegraph.co.uk/news/main.jhtml?xml=/news/2007/08/0...

Physicists have 'solved' mystery of levitation

By Roger Highfield, Science Editor
Last Updated: 1:41am BST 08/08/2007

Levitation has been elevated from being pure science fiction to science fact, according to a study reported today by physicists.

In earlier work the same team of theoretical physicists showed that invisibility cloaks are feasible.

Now, in another report that sounds like it comes out of the pages of a Harry Potter book, the University of St Andrews team has created an 'incredible levitation effects' by engineering the force of nature which normally causes objects to stick together.

Professor Ulf Leonhardt and Dr Thomas Philbin, from the University of St Andrews in Scotland, have worked out a way of reversing this phenomenon, known as the Casimir force, so that it repels instead of attracts.

Their discovery could ultimately lead to frictionless micro-machines with moving parts that levitate But they say that, in principle at least, the same effect could be used to levitate bigger objects too, even a person.

In theory the discovery could be used to levitate a person

The Casimir force is a consequence of quantum mechanics, the theory that describes the world of atoms and subatomic particles that is not only the most successful theory of physics but also the most baffling.

The force is due to neither electrical charge or gravity, for example, but the fluctuations in all-pervasive energy fields in the intervening empty space between the objects and is one reason atoms stick together, also explaining a "dry glue" effect that enables a gecko to walk across a ceiling.

Now, using a special lens of a kind that has already been built, Prof Ulf Leonhardt and Dr Thomas Philbin report in the New Journal of Physics they can engineer the Casimir force to repel, rather than attact.

Because the Casimir force causes problems for nanotechnologists, who are trying to build electrical circuits and tiny mechanical devices on silicon chips, among other things, the team believes the feat could initially be used to stop tiny objects from sticking to each other.

Prof Leonhardt explained, "The Casimir force is the ultimate cause of friction in the nano-world, in particular in some microelectromechanical systems.

Such systems already play an important role - for example tiny mechanical devices which triggers a car airbag to inflate or those which power tiny 'lab on chip' devices used for drugs testing or chemical analysis.

Micro or nano machines could run smoother and with less or no friction at all if one can manipulate the force." Though it is possible to levitate objects as big as humans, scientists are a long way off developing the technology for such feats, said Dr Philbin.

The practicalities of designing the lens to do this are daunting but not impossible and levitation "could happen over quite a distance".

Prof Leonhardt leads one of four teams - three of them in Britain - to have put forward a theory in a peer-reviewed journal to achieve invisibility by making light waves flow around an object - just as a river flows undisturbed around a smooth rock.

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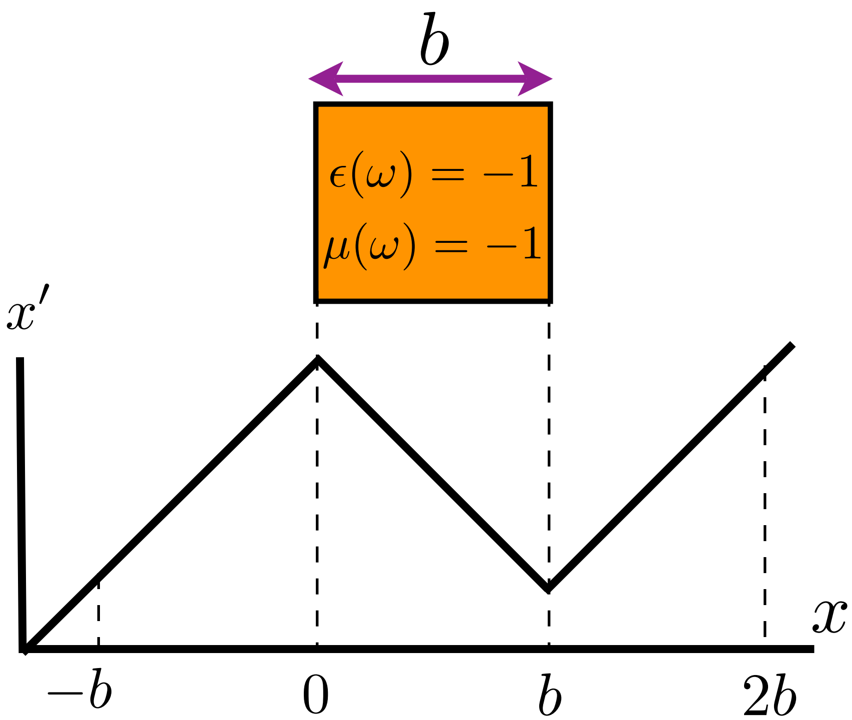
"In theory the discovery could be used to levitate a person"

Quantum levitation with MMs?

Transformation media

Leonhardt et al (2007)

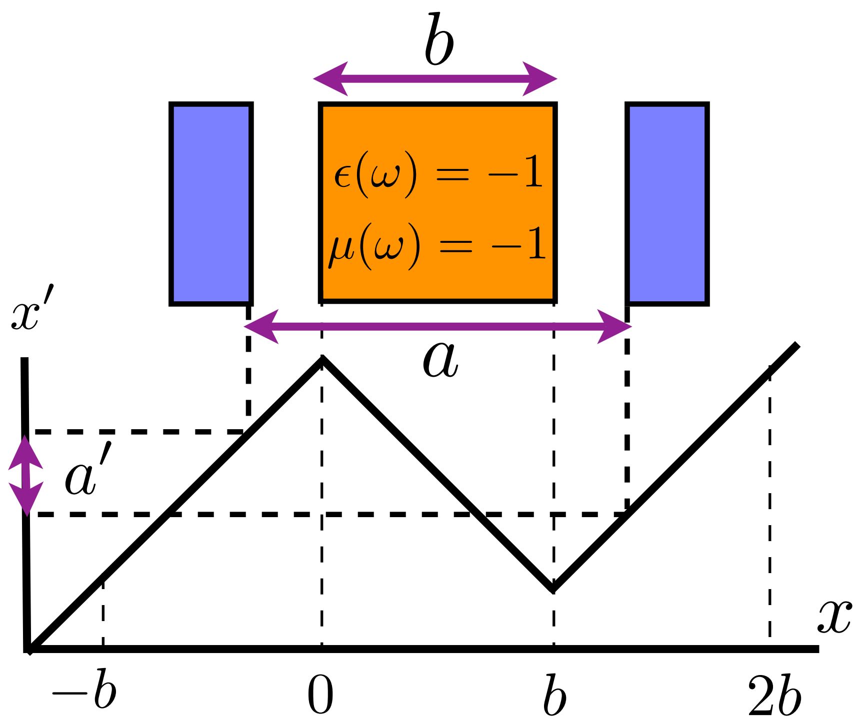


Perfect lens: EM field in -b<x<0 is mapped into x'. There are two images, one inside the device and one in b<x<2b.

Quantum levitation with MMs?

Transformation media

Leonhardt et al (2007)



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Casimir cavity: $a' = |a - 2b|$

When a< 2b (plates within the imaging range of the perfect lens)

$$\Rightarrow f = -\frac{\partial U}{\partial a'}\frac{\partial a'}{\partial a} = +\frac{\hbar c \pi^2}{240 a'^4} \Rightarrow$$ Repulsion

Quantum levitation with MMs?

Transformation media

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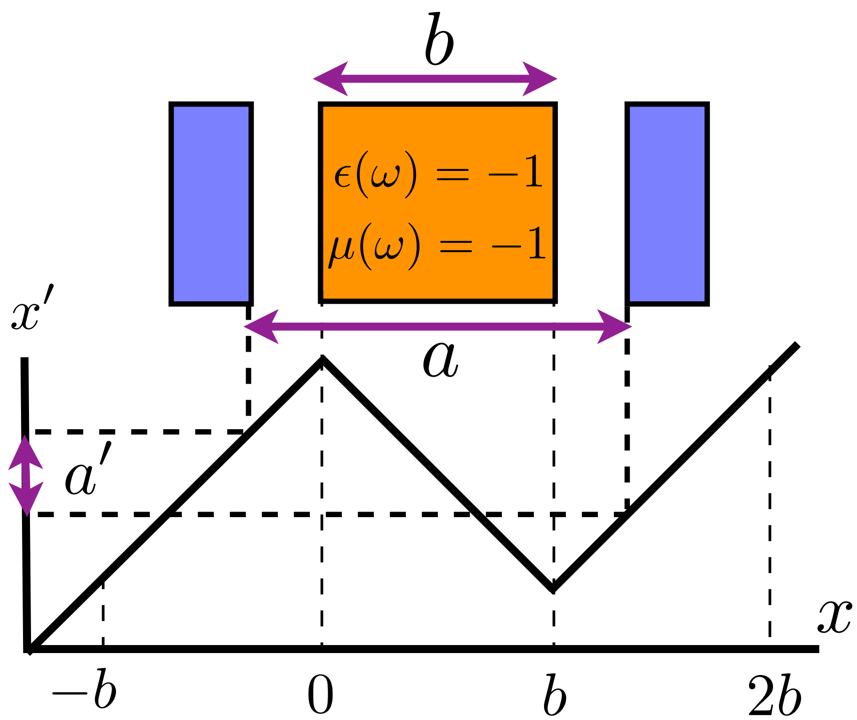

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For real materials, however .....

- According to causality, no passive medium ($\epsilon''(\omega) > 0$) can sustain $\epsilon, \mu \simeq -1$ over a wide range of frequencies. In fact, $\epsilon(i\xi), \mu(i\xi) > 0$
- Another proposal is to use an active MM ($\epsilon''(\omega) < 0$) in order to get repulsion. But then the whole approach breaks down, as real photons would be emitted into the quantum vacuum.

Metamaterials for Casimir

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Drude-Lorentz model:

$$\epsilon_\alpha(\omega) = 1 - \frac{\Omega_{E,\alpha}^2}{\omega^2 - \omega_{E,\alpha}^2 + i\Gamma_{E,\alpha}\omega}$$

$$\mu_\alpha(\omega) = 1 - \frac{\Omega_{M,\alpha}^2}{\omega^2 - \omega_{M,\alpha}^2 + i\Gamma_{M,\alpha}\omega}$$

Typical separations

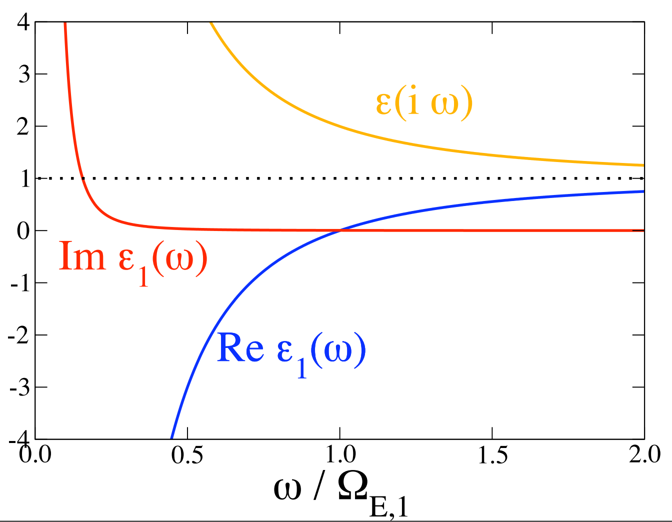
$d = 200 - 1000 \text{ nm}$

Infrared-optical frequencies

$\Omega/2\pi = 5 \times 10^{14}\text{Hz}$

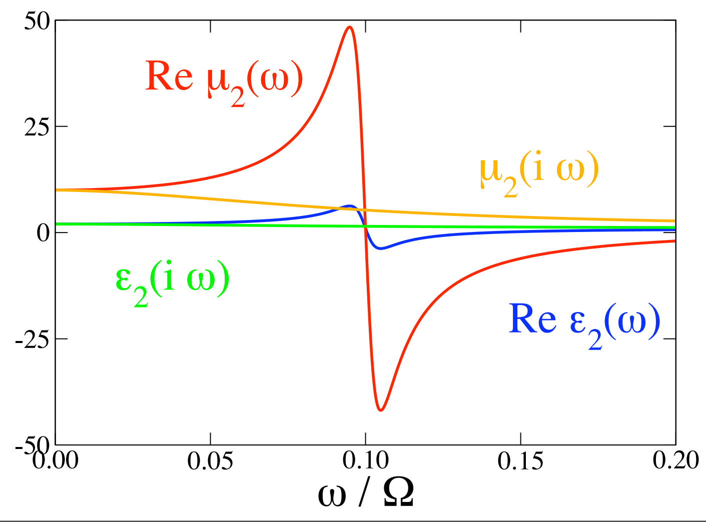
Drude metal (Au)

$\Omega_E = 9.0 \text{ eV} \quad \Gamma_E = 35 \text{ meV}$



Metamaterial

$\text{Re } \epsilon_2(\omega) < 0 \quad \text{Re } \mu_2(\omega) < 0$



$\Omega_{E,2}/\Omega = 0.1 \quad \Omega_{M,2}/\Omega = 0.3$

$\omega_{E,2}/\Omega = \omega_{M,2}/\Omega = 0.1$

$\Gamma_{E,2}/\Omega = \Gamma_{M,2}/\Omega = 0.01$

$\epsilon(i\xi) < \mu(i\xi)$

Attraction-repulsion crossover

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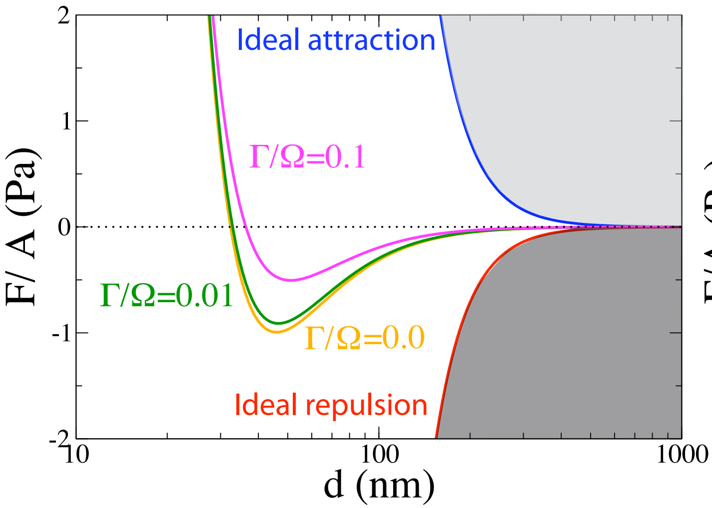
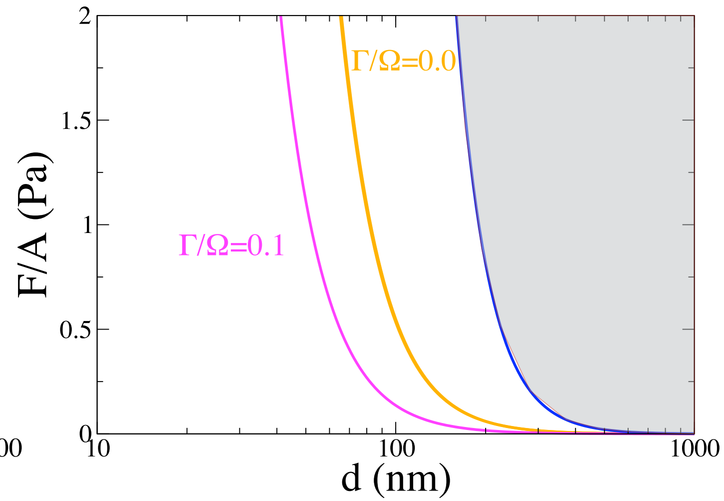
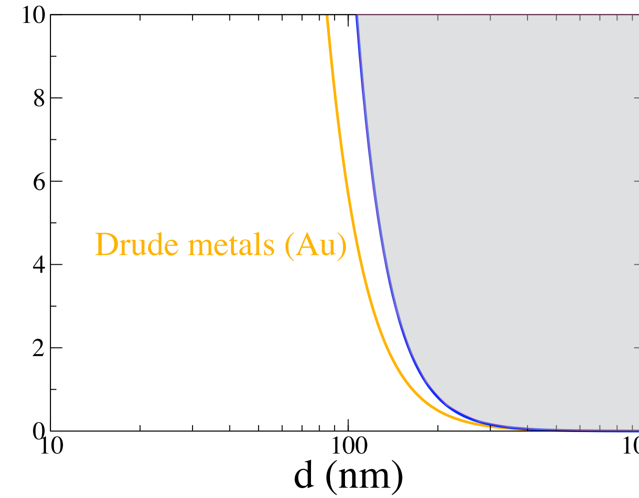
Drude metal (Au)	Metamaterial	Drude metal (Au)
Metamaterial	Metamaterial	Drude metal (Au)







Repulsion-attraction | Only attraction | Only attraction

A slab made of Au ($\rho = 19.3\ \mathrm{gr/cm^3}$) of width $\delta = 1\mu\mathrm{m}$ could levitate in front of one of these MMs at a distance of $d \approx 110\ \mathrm{nm}$!!!

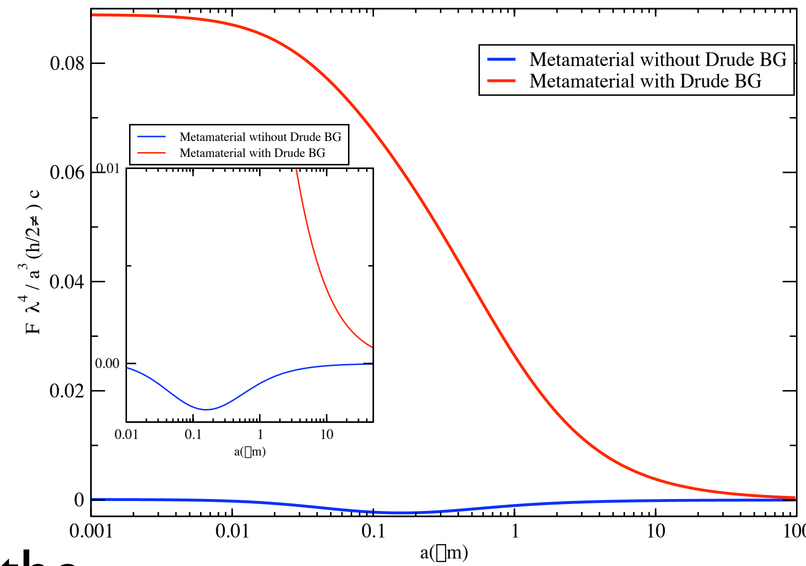
Casimir and metamaterials, Henkel et al (2005)

Casimir and surface plasmons, Intravaia et al (2005)

van der Waals in magneto-dielectrics, Spagnolo et al (2007)

Some other important issues...

Effects of Drude background



$$\epsilon(i\xi) = 1 + \boxed{\frac{\Omega_D^2}{\xi^2 + \Gamma_D \xi}} + \boxed{\frac{\Omega_E^2}{\xi^2 + \omega_E^2 + \Gamma_E \xi}}$$

Drude part MM resonance

As the Drude background may overwhelm the resonant contribution in the low frequency limit, it may kill repulsion completely! $\rightarrow$ $\epsilon(i\xi) > \mu(i\xi)$

Some other important issues...

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Effects of Drude background

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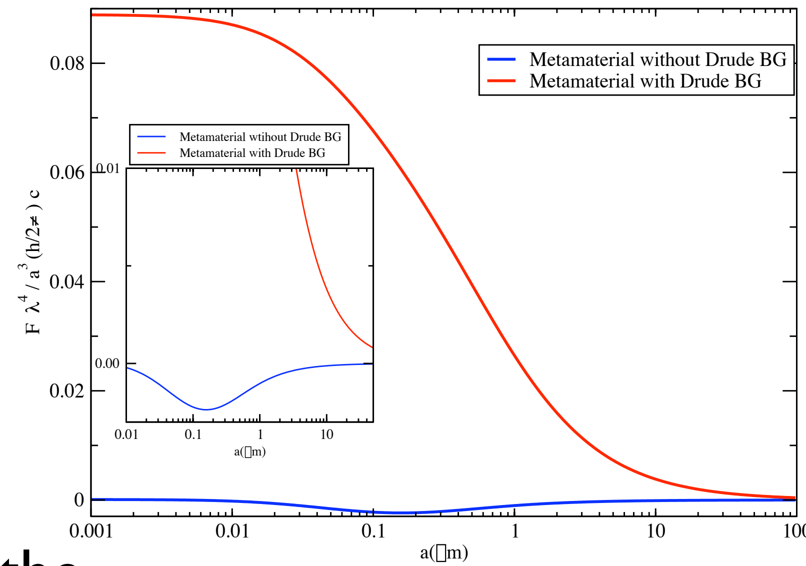
Drude part   MM resonance



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Effects of MM anisotropy

It is possible to derive a more complicated Lifshitz formula for continuous, anisotropic magneto-dielectric materials $\epsilon_{ij}(\omega)$ $\mu_{ij}(\omega)$

Anisotropy typically reduces the magnitude of the possible Casimir repulsion, as compared to an ideally isotropic metamaterial

Conclusions

- In principle, metamaterials can strongly influence the quantum vacuum, providing a route towards quantum levitation.

- However, we believe that previous works have been overly optimistic about the feasibility of quantum levitation via MMs.

- We have analyzed new important effects influencing Casimir repulsion in metamaterials:

  - Non-resonant optical response (Drude background)
  - Anisotropic permittivities and/or permeabilities
  - Different models for optical response (Drude, Drude-Lorentz, etc)